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(54) **HETEROGENEOUS THIOL-ENE CLICK MODIFICATIONS OF SOLID POLYSACCHARIDE-BASED MATERIALS**

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CPC . **C08B 3/08** (2013.01); **C08B 3/14** (2013.01);

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(58) **Field of Classification Search**

None

See application file for complete search history.

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ABSTRACT

This invention concerns the first environmentally benign heterogeneous modification of polysaccharide-based material in native solid state by thiol-ene "click chemistry". The direct reaction of a thiol with an un-activated double or triple bond by thiol-ene and thiol-ene click modification is thermally or photochemically catalyzed and is completely metal-free and allows for a highly modular approach to modifications of fibers and fiber-based materials.

8 Claims, 1 Drawing Sheet

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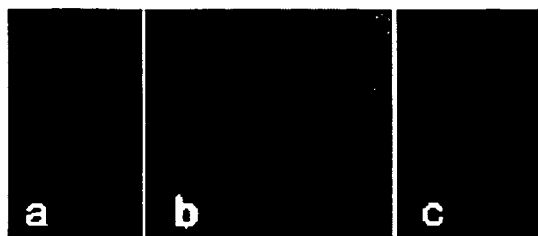


Fig. 1

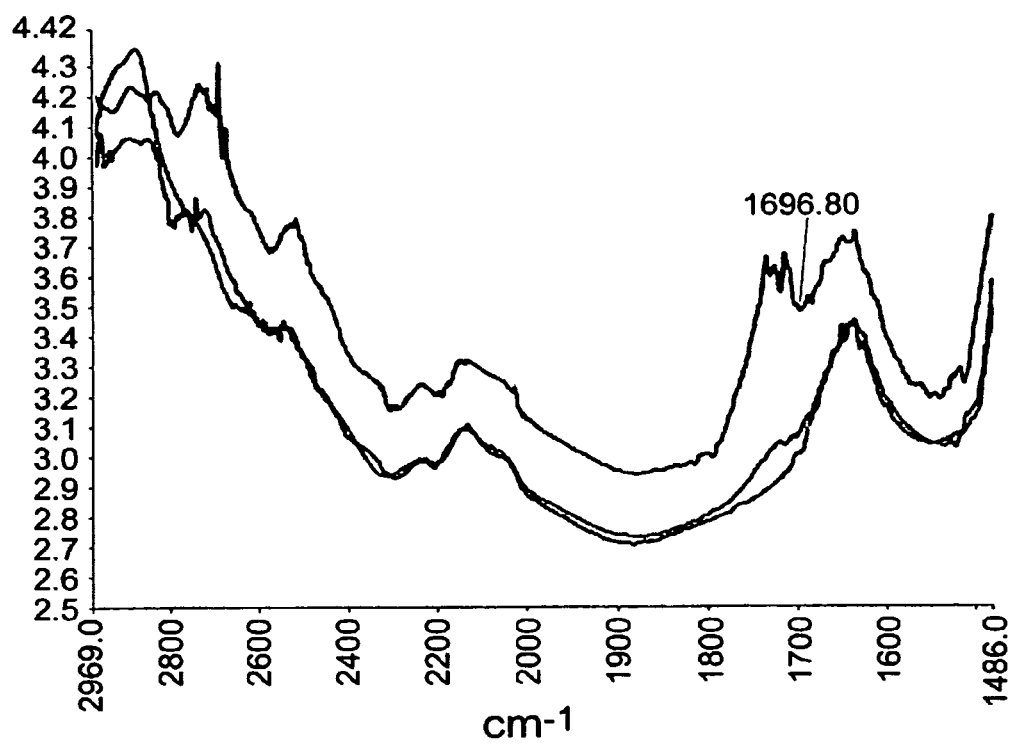


Fig. 2

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HETEROGENEOUS THIOL-ENE CLICK MODIFICATIONS OF SOLID POLYSACCHARIDE-BASED MATERIALS

CROSS REFERENCE TO RELATED APPLICATION

This is a divisional application of U.S. patent application Ser. No. 13/522,067, filed Jul. 13, 2012, which is a national phase of International Application No. PCT/SE2011/050058 filed Jan. 19, 2011, which claims priority to U.S. 61/296,161 filed Jan. 19, 2010.

FIELD OF INVENTION

The present invention relates to a highly modular method for heterogeneous modification of polysaccharide-based materials in native solid state by the reaction between a sulfide and an alkene or an alkyne.

BACKGROUND

The development of polymeric materials with tailored surface properties plays an important role in today's society. Essential all devices and carriers contain different materials that have to be compatible with their surroundings. In addition, there is a need to develop chemistry that is based on renewable resources. Polysaccharides are a natural and renewable resource and a desirable raw material for sustainable chemistry applications. Chemical modifications of polysaccharides are often an important step to change its chemistry or structure in order to design properties needed for specific applications.^[1,2] Esterification and etherification are among the most commonly used derivatizations of polysaccharides. There is much use of, and many reports on, efficient and homogenous derivatization of dissolved polysaccharides, but less on solid polysaccharides, such as cellulose. There are different technically viable approaches for cellulose modifications using, for example, acid chlorides, anhydrides and heavy metal based catalyst or nucleophilic substitutions. However, direct, inexpensive, technically simple, environmentally friendly and modular modifications of solid carbohydrates are of great interest to many industries utilizing natural fibers, but it is a challenging task due to the low reactivity of the solid surface of native cellulose and polysaccharide-based materials.^[3] So called "Click" chemistry,^[5] (copper(I)-catalyzed Huisgen 1,3-dipolar cycloaddition between azides and terminal alkynes)^[6] have been applied to polysaccharides and allow for chemoselective and highly modular route to cellulose modifications.^[7,8] The reaction of a thiol with an un-activated double bond has been used in various applications to crosslink polymers and has recently emerged as a new thiol-ene based "click" chemistry coupling reaction providing for chemo-selective bio-conjugations and polymerizations.^[9-11] The thiol-ene "click" reaction does not require the need for a metal catalyst as compared with for example the copper(I)-mediated azide/alkyne click chemistry. Thiol-ene coupling also benefits from that it can be activated both thermally or photochemically and, depending on substrates, performed without solvents allowing for green and efficient reaction conditions.^[12]

This invention provides the first example of the environmentally benign heterogeneous modification of polysaccharide-based materials in its native solid state by thiol-ene

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"click chemistry". This "organoclick" methodology is highly modular and completely metal-free.

OBJECT OF THE INVENTION

It is an object of the invention to provide a highly modular method for the heterogeneous modification of polysaccharide-based materials (plant material or plant derived-fibers, solid-(ligno)cellulose, hemicellulose, starch or any solid state polysaccharide-containing polymer alone or within a matrix) in native solid state by the reaction of a thiol with a double or triple bond by thiol-ene and thiol-ene click modification.

Another object of the invention is to provide a highly modular method for the heterogeneous modification of polysaccharide-based materials comprising or substantially consisting of cellulose fiber in native solid state by the reaction of a thiol with a double or triple bond by thiol-ene and thiol-ene click modification.

Another object of the invention is to attach a small molecule (e.g. fluorophores, UV active molecules, drug, amino acid, catalyst) by the method of the invention.

An additional object is to attach a large molecule (e.g. polymer, peptide, polymer) by the method of the invention.

A still further object of the method is to provide a method of the aforementioned kind that is advantageous from an environmental and health standpoint.

Even more objectives will become evident from a study of the summary of the invention, a number of preferred embodiments illustrated in a drawing, and the appended claims.

DESCRIPTION OF THE SCHEMES AND FIGURES

Scheme 1 is a picture illustrating the "thiol-ene" reaction or "thiol-ene" reaction between a heterogeneous polysaccharide with thiol groups and an alkene or an alkyne, respectively.

Scheme 2 is a picture illustrating the "thiol-ene" reaction or "thiol-ene" reaction between a heterogeneous polysaccharide with alkene or alkyne groups with a thiol, respectively.

Scheme 3 is a picture illustrating examples of molecules that were attached to cellulose modified with alkenes.

FIG. 1 shows the fluorescence of cellulose 2a, cellulose 4aa and cellulose were the fluorescent molecule has been removed by hydrolysis.

FIG. 2 shows the IR spectra of cellulose (blank), cellulose 2a and cellulose 4ab.

SUMMARY OF THE INVENTION

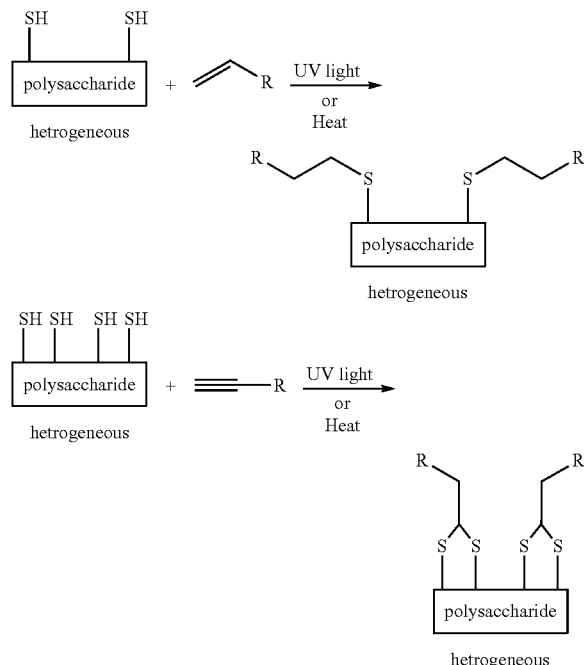
The invention is based on the use of heat or light as activation agents for the conjunction of a solid polysaccharide-based material carrying a terminal thiol-group with another molecule (monomer, oligomer or polymer) containing a terminal unsaturated double or triple bond via a thiol-ene click-chemistry type reaction. And the reverse case also apply, with a solid polysaccharide-based material carrying an alkene or alkyne hydrocarbon bond reacting with a molecule (monomer, oligomer, protein, biotine, peptide, amino acid, small molecule, drug or polymer) containing a terminal thiol-group via a thiol-ene click-chemistry type reaction.

One aspect of the invention is that a solid polysaccharide-based material ((plant material or plant derived-fibers, solid-

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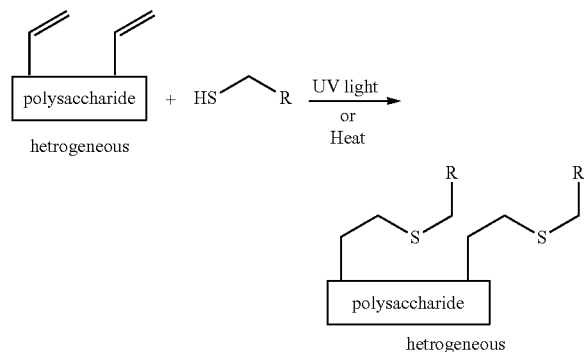
(ligno)cellulose, hemicellulose, starch or any solid state polysaccharide-containing polymer alone or within a matrix)) with a terminal thiol group reacts with another molecule (monomer, oligomer or polymer) carrying a terminal unsaturated (double or triple) hydrocarbon bond using either photon irradiation or heat, or in combination, as catalyst obtaining the corresponding thiol-ene linked modified products (according to Scheme 1).

Scheme 1.



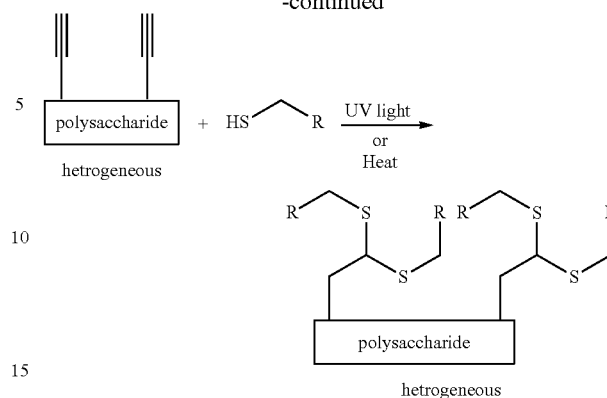
Another aspect of the invention is that a solid polysaccharide-based material ((plant material or plant derived-fibers, solid-(ligno)cellulose, hemicellulose, starch or any solid state polysaccharide-containing polymer alone or within a matrix)) with a terminal unsaturated (double or triple) hydrocarbon bond reacts with another molecule (monomer, oligomer or polymer) carrying terminal thiol group using either photon irradiation or heat, or in combination, as catalyst obtaining the corresponding thiol-ene linked modified products (according to Scheme 2).

Scheme 2.



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-continued



Another aspect of the invention is that all the previously described transformations can be and are performed with an enantiomerically pure reactants yielding enantiomerically pure products.

Another aspect of the invention is that polysaccharide-based fiber material initially without thiol- or olefinic groups may be substituted with a terminal thiol- or olefinic containing molecule by organocatalytic derivatization of polysaccharide-based fiber material using small organic acids as catalysts according a previous patent (International Patent WO 2006068611 A1 20060629 "Direct Homogeneous and Heterogeneous Organic Acid and Amino Acid-Catalyzed Modification of Amines and Alcohols"). Thereby, a completely metal-free, environmentally friendly and highly modular modification of any solid polysaccharide-based fibrous material may be achieved.

Another aspect of the invention is that polysaccharide-based fiber material initially without olefinic groups may be substituted with a terminal olefinic containing molecule by derivatization of polysaccharide-based fiber material using acrylic and methacrylic anhydrides with or without a nucleophilic catalyst. Thereby, a completely metal-free, environmentally friendly and highly modular modification of any solid polysaccharide-based fibrous material may be achieved.

The method of the invention is composed of two steps in which the heterogeneous polysaccharide is modified under environmentally benign conditions. In one embodiment of the invention the method comprises the steps of:

- i) Providing a heterogeneous polysaccharide
- ii) Chemically modify said polysaccharide with a molecule containing an alkene or alkyne group by a suitable modification method.
- iii) To the alkene or alkyne group on the modified heterogeneous polysaccharide attach a thiol-containing functional molecule by using thiol-ene and thiol-alkyne click modification, respectively, using UV irradiation, heat or a Michael conjugate addition.

In another embodiment of the invention the method comprises the steps of:

- iv) Providing a heterogeneous polysaccharide
- v) Chemically modify said polysaccharide with a molecule containing a thiol group by a suitable modification method.
- vi) To the thiol group on the modified heterogeneous polysaccharide attach an alkene- or alkyne-containing functional molecule by using thiol-ene and thiol-alkyne click modification, respectively, using UV irradiation, heat or a Michael conjugate addition.

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Suitable reactive molecules that may be used in order to attach the alkene, alkyne, or thiol group to the heterogeneous polysaccharide in the second step of the invention include acids, alkyl ketene dimers, acid chlorides, epoxides, akoxysilanes, chlorosilanes, anhydrides, or other reactive molecules containing the alkene, alkyne or thiol functionality. The modification may be performed in a water based solution, in an organic solvent or neat. The modification may be performed with or without a catalyst. Suitable catalysts, depending on the nature of the reactive molecule, may be an acid catalyst, or a nucleophilic catalyst. The nature of the catalyst for the specific reactive molecule may be determined by a person skilled in the art.

In the third step of the invention, a thiol-, alkene-, or alkyne-containing molecule is linked to the previously attached thiol, alkene- or alkyne containing molecule used in step two of the invention by thiol-ene and thiol-ene click modification, respectively, using UV irradiation, heat or a Michael conjugate addition as previously described.

Heterogeneous polysaccharides modified by using the method of the invention may be for example modified cellulosic fibres, modified starches, or modified hemicelluloses. The materials may be polymers or individual fibres, but may also be in form of a matrix or web such as for example a paper based material, cotton based textile, non-woven textile, or wood based material, such as for example particle board, MDF-board, or solid wood.

DETAILED DESCRIPTION

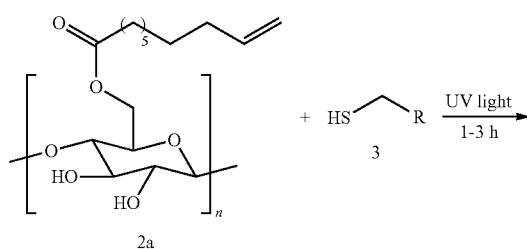
Thiol-Ene Click Derivatization of Cellulose

To a solution of a thiol ((with 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %)) around 30 mg cellulose (containing terminal olefinic groups) was added (see Scheme 3). Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. After that, the cellulose was taken out and purified by soxhlet extraction. After drying the thiol-ene click modified cellulose was obtained. The cellulose was modified with polyesters, aliphatic and aryl groups. The cellulose was also modified with the amino acid cystein.

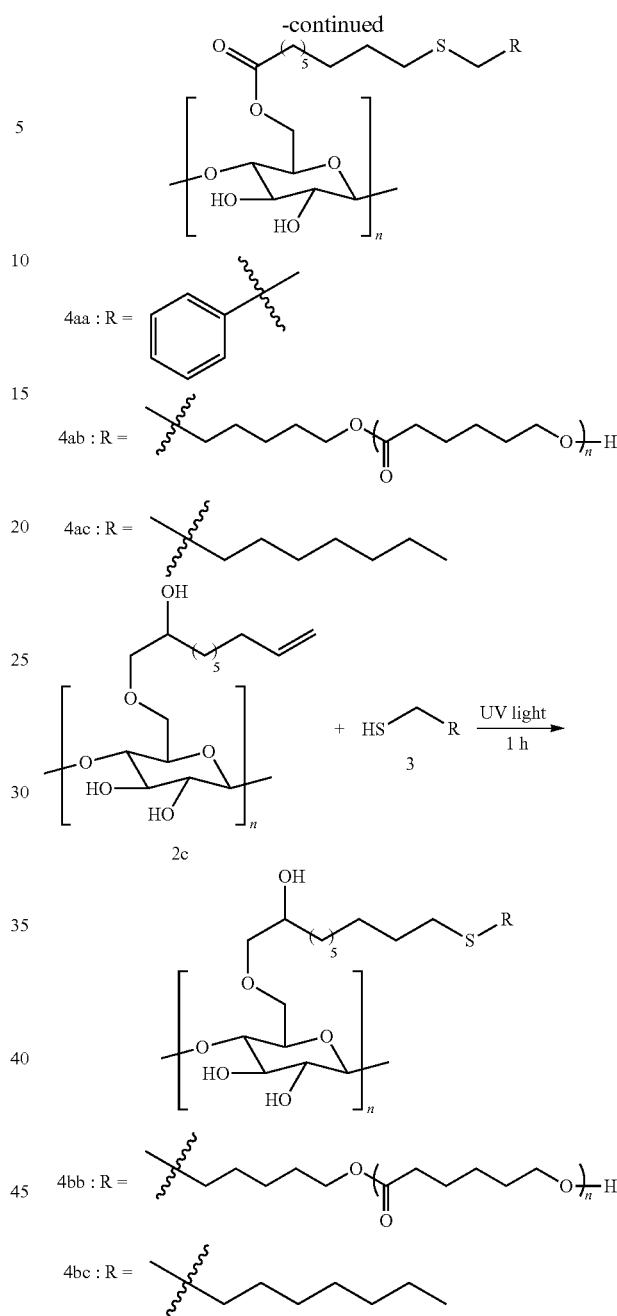
Sample Analyses

The cellulose samples derivatized by polyesters or hydrocarbons were analyzed using FT-IR, directly without further sample handling, using a Perkin-Elmer Spectrum One FT-IR spectrophotometer. Each sample was subject to 32 averaged scans. Fluorescence of benzyl-derivatized cellulose samples were analyzed using a Leica fluorescence microscope with an excitation/emission filter cub (filter cub A); excitation (λ_{ex})=340-380 nm and emission (λ_{em})>425 nm using 10x objective lens.

Scheme 3.



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The present invention will now be described by reference to a number of preferred embodiments illustrated in the following Examples.

Example 1

The filter paper (around 30 mg) was dipped into a mixture of 9-decanoic acid (1 g) and (S)-tartaric acid (5 mol %). Then the reaction was heated to 110° C. and kept for 8 hours. After that, the filter paper was taken out and extracted by soxhlet. After drying the modified filter paper 2a (Scheme 3) was obtained.

Example 2

The filter paper (around 30 mg) was dipped into a mixture of hex-5-ynoic acid (1 g) and (S)-tartaric acid (5 mol %).

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Then the reaction was heated to 110° C. and kept for 8 hours. After that, the filter paper was taken out and extracted by soxhlet. After drying the modified filter paper 2b was obtained.

Example 3

The filter paper (around 30 mg) was dipped into a mixture of 2-(oct-7-enyl)oxirane (1 g) and (S)-tartaric acid (5 mol %). Then the reaction was heated to 110° C. and kept for 1 hour. After that, the filter paper was taken out and extracted by soxhlet. After drying the modified filter paper 2c (Scheme 3) was obtained.

Example 4

To a mixture of the 9-decenoic acid (340 mg, 2 mmol) and octane-1-thiol (292 mg, 2 mmol) was added 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %). Then the reaction mixture was irradiated with UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. The product was formed as a white solid and checked by ¹H NMR.

10-(Octylthio)decanoic acid: ¹H NMR (400 MHz, CDCl₃) δ 2.51 (t, J=6.0 Hz, 4H), 2.36 (t, J=6.0 Hz, 2H), 1.66-1.56 (m, 6H), 1.38-1.29 (m, 20H), 0.89 (t, J=5.6 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 180.6, 34.2, 32.3, 32.2, 31.9, 29.82, 29.78, 29.4, 29.32, 29.29, 29.13, 29.08, 29.0, 28.5, 24.7, 22.8, 14.2.

Example 5

To a solution of the benzylthiol with 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2a (around 30 mg) was added. Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. After that, the cellulose was taken out and purified by soxhlet. After drying the modified cellulose 4aa was obtained. The cellulose 4aa exhibited fluorescence, which is in agreement with the attachment of the benzyl thiol to the cellulose FIG. 1.

FIG. 1. The fluorescence of 9-decenoic acid modified cellulose 2a (a), fluorescent-labeled cellulose 4aa (b), and sample 4aa after deesterification (NaOH) and subsequent extraction to remove the released molecules (c).

Example 6

To a bulk solution of the polymer (poly(ε-caprolactone (PCL)) with a thiol end-group and 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2a (around 30 mg) was added. Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. After that, the cellulose was taken out and purified by soxhlet. After drying the polymer-modified cellulose 4ab was obtained. The cellulose 4ab was analyzed by IR (FIG. 2).

FIG. 2. FT-IR spectra: the top line is the IR of the modified cellulose 4ab, the middle one is the IR spectrum of 2a, the lowest line is the IR of the blank. The ester carbonyl (C=O) absorbs at 1730 cm⁻¹.

Example 7

To a solution of the octane thiol with 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2a (around 30 mg) was added. Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20 W/12, 20 W)

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for 1 h. After that, the cellulose was taken out and purified by soxhlet. After drying the modified cellulose 4ac was obtained.

Example 8

To a solution of the benzylthiol with 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2c (around 30 mg) was added. Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. After that, the cellulose was taken out and purified by soxhlet. After drying the modified cellulose was obtained. The cellulose exhibited fluorescence, which is in agreement with the attachment of the benzyl thiol.

Example 9

To a bulk solution of the polymer (poly(ε-caprolactone (PCL)) with a thiol end-group and 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2c (around 30 mg) was added. Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. After that, the cellulose was taken out and purified by soxhlet. After drying the polymer-modified cellulose 4bb was obtained.

Example 10

To a solution of the octane thiol with 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2c (around 30 mg) was added. Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. After that, the cellulose was taken out and purified by soxhlet. After drying the modified cellulose 4bc was obtained.

Example 11

To a bulk solution of the polymer (poly(ε-caprolactone (PCL)) with a thiol end-group and 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2c (around 30 mg) was added. Then the reaction was heated at 80° C. for 16 h. After that, the cellulose was taken out and purified by soxhlet. After drying the polymer-modified cellulose 4bb was obtained.

Example 12

To a bulk solution of the polymer (poly(ε-caprolactone (PCL)) with a thiol end-group and 2,2-dimethoxy-2-phenylacetophenone (DMPA) (1 wt %) the modified cellulose 2b (around 30 mg) was added. Then the reaction was irradiated with a UV lamp (UV-B bulb, TL20W/12, 20 W) for 1 h. After that, the cellulose was taken out and purified by soxhlet. After drying the polymer-modified cellulose 4cc was obtained.

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The invention claimed is:

1. A method for the heterogeneous modification of solid polysaccharide-based material comprising the steps of
 - (ib) providing a solid polysaccharide-based material with terminal double or triple unsaturated hydrocarbon bonds; and
 - (iib) bringing said terminal double or triple unsaturated hydrocarbon bonds to react with a molecule containing a terminal thiol group,
 wherein the solid polysaccharide-based material with double or triple unsaturated hydrocarbon bonds is provided by
 - (i) providing a solid polysaccharide-based material;
 - (ii) providing a modifying agent comprising double or triple unsaturated hydrocarbon bonds;
 - (iii) optionally providing a catalyst which is an acid catalyst, or a nucleophilic catalyst; and
 - (iv) reacting the solid polysaccharide-based material with the modifying agent, optionally in the presence of said catalyst,
 wherein the modifying agent comprising double or triple unsaturated hydrocarbon bonds is chosen from among acids, alkyl ketene dimers, acid chlorides, epoxides, alkoxy silanes, chlorosilanes, and anhydrides containing alkene or alkyne functionality.
2. The method according to claim 1 in which said double or triple unsaturated hydrocarbon bonds are brought to a click-chemistry type reaction with the molecule containing a thiol-group by using either photon irradiation or heat, or a combination thereof, as catalyst.
3. The method according to claim 1 in which said double or triple unsaturated hydrocarbon bonds are brought to a click-chemistry type reaction with the molecule containing a thiol-group by way of Michael conjugate addition.
4. The method according to claim 1 in which said molecule containing a thiol-group is a molecule of a substance chosen from among dyes, fluorescent substances, polymers, amino acids, peptides, proteins, UV-active substances, biotin, antibodies, and substances containing alkyl groups.
5. The method according to claim 1 in which said molecule containing a thiol-group is a molecule of a substance which is provided in nano particle size or quantum dot particle size.
6. The method according to claim 1 in which said optional catalyst is an amino acid, a peptide or a derivative thereof, an oligopeptide, H₂O, a sulfonic acid, a tetrazole or an organic acid.
7. The method according to 1, wherein said solid polysaccharide-based material comprises cellulosic fibers, cellulose derivatives, lignocelluloses, hemicelluloses, starches, starch derivatives, or any combination thereof.
8. The method according to claim 4 in which said thiol-group containing polymer is a polyester.

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